

Gamma-Spectrum Generator



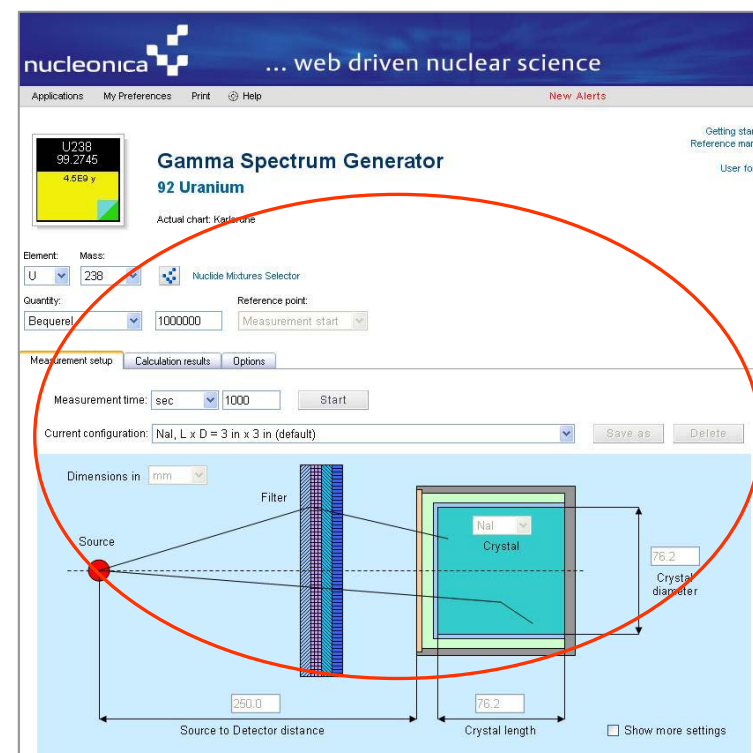
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Outline

- **Introduction**
- **Simulation approach**
- **Features implemented**
- **Some examples**
- **Current & Future work**
- **Exercises**

Introduction: Potential Applications of the GSG

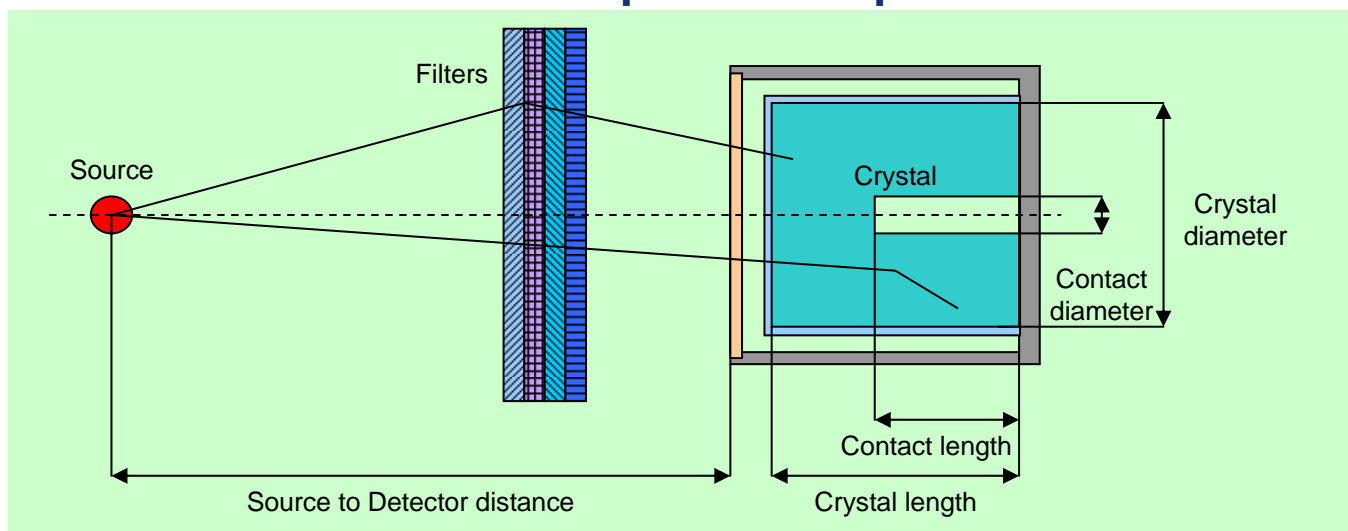
Education & Training:

- Nuclear and radio-chemists
- Health physicists
- Nuclear facility operators
- Radiation protection staff
- Nuclear safeguards inspectors
- Experts involved in the illicit trafficking incidents and consequence management

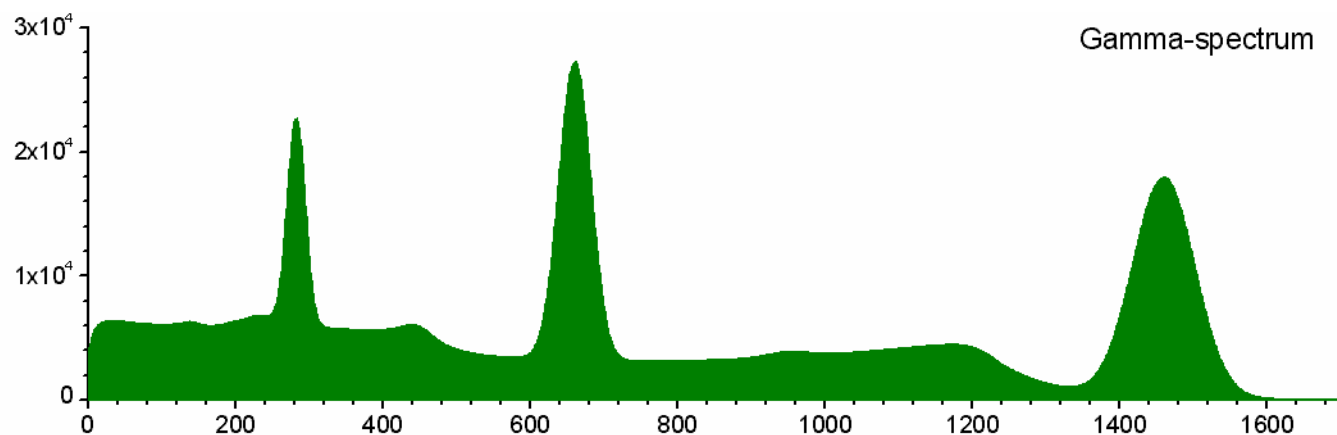
Real Applications:

- Illicit trafficking incidents involving heavily shielded & volume sources: quick and reliable evaluation of self-attenuation and shielding corrections
- Instrumentation, software & measurement techniques development: detection limits, unusual/unavailable nuclide mixtures, special measurement conditions etc.
- Gamma-spectrum evaluation using full spectrum processing approach

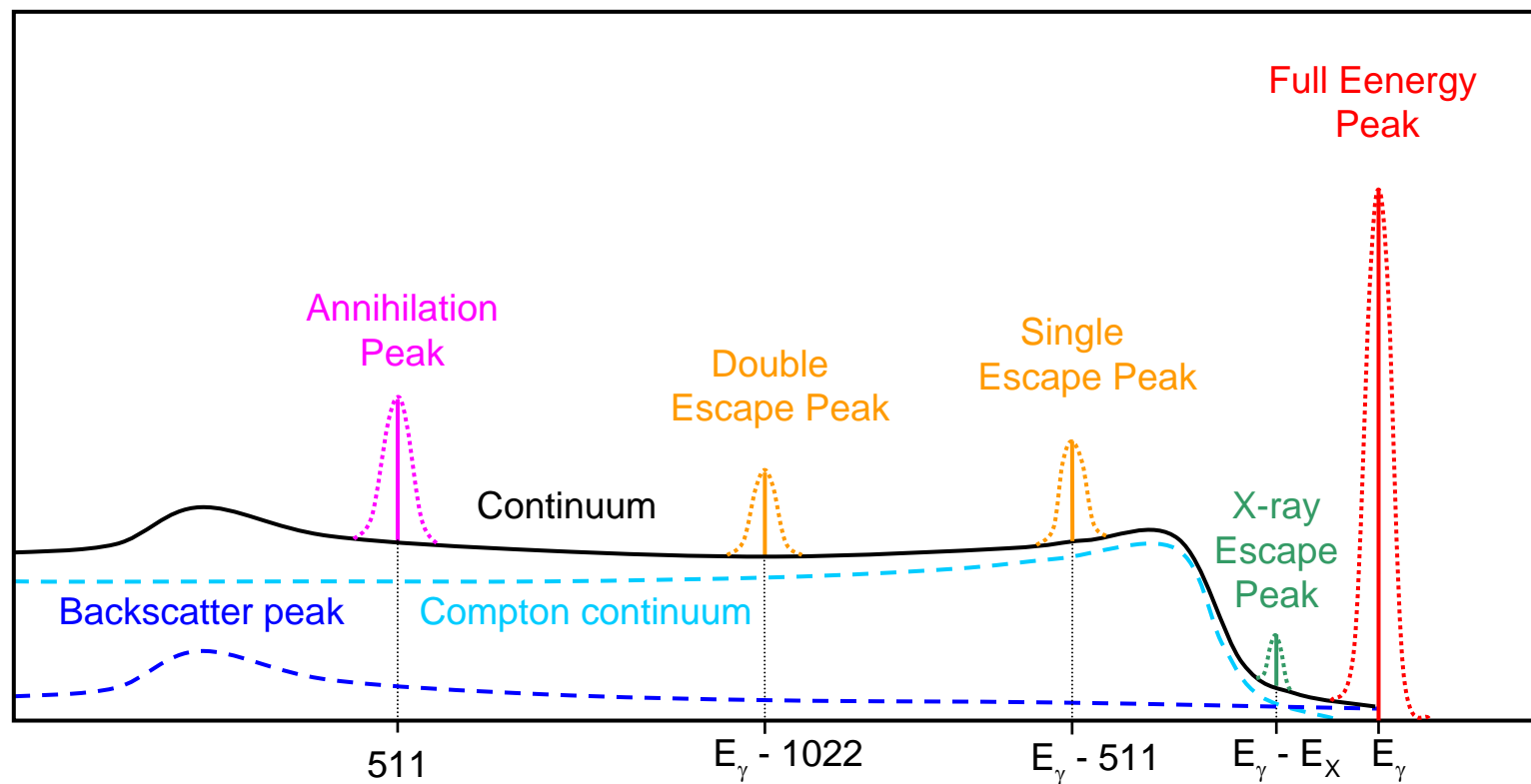
Measurement setup model implemented:



Spectrum modeling procedure:



Detector response profile model:



Detector Reference Response Profile DATABASE:

Method:

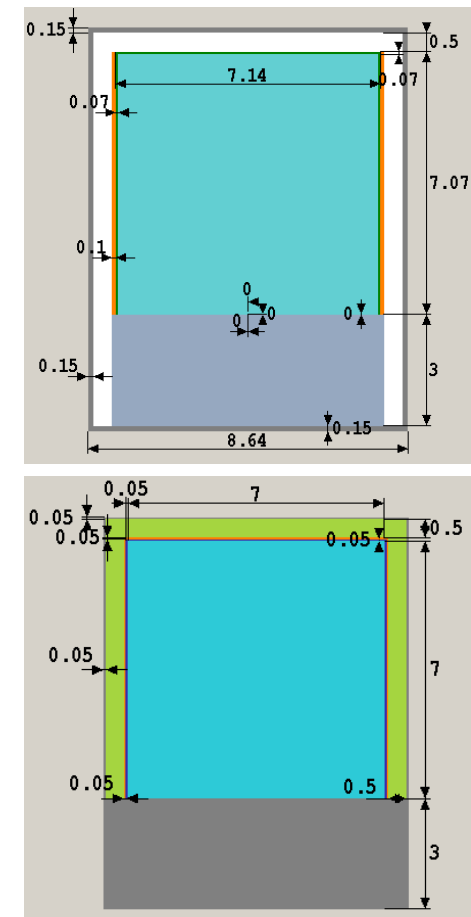
- **Monte Carlo** simulation using specially developed and validated program – DRGen (*Detector Response Generator*)

Content:

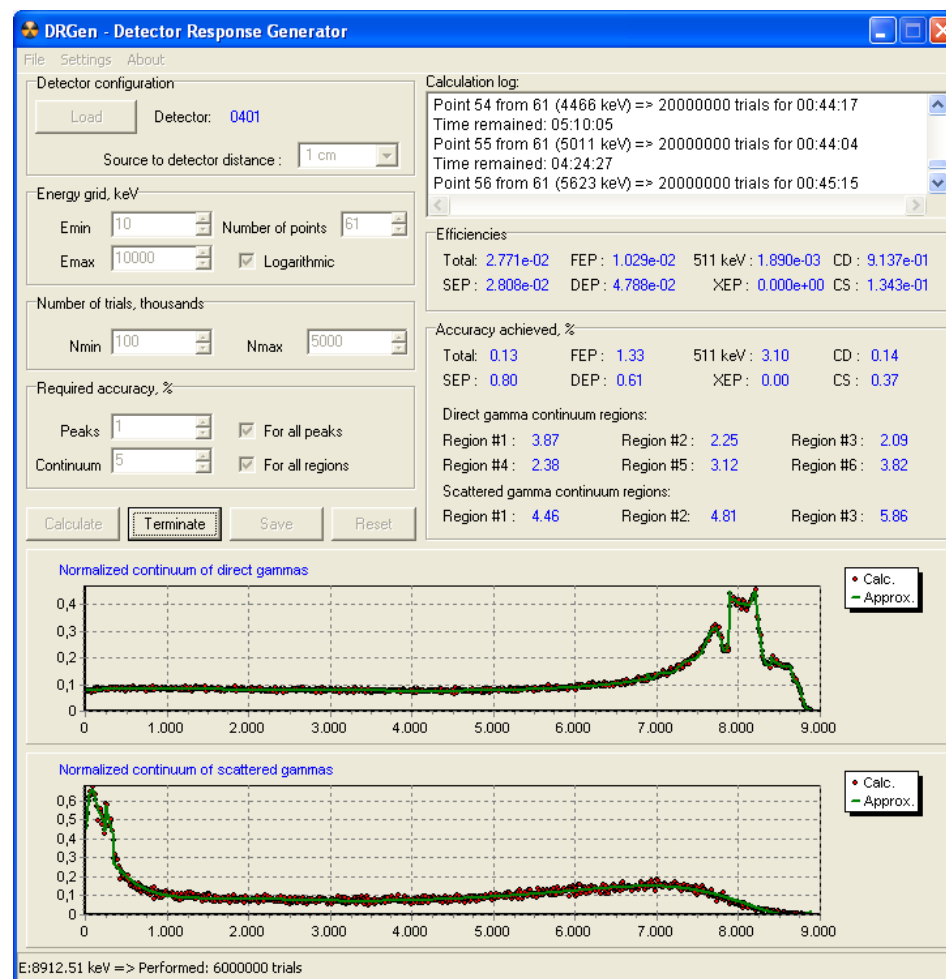
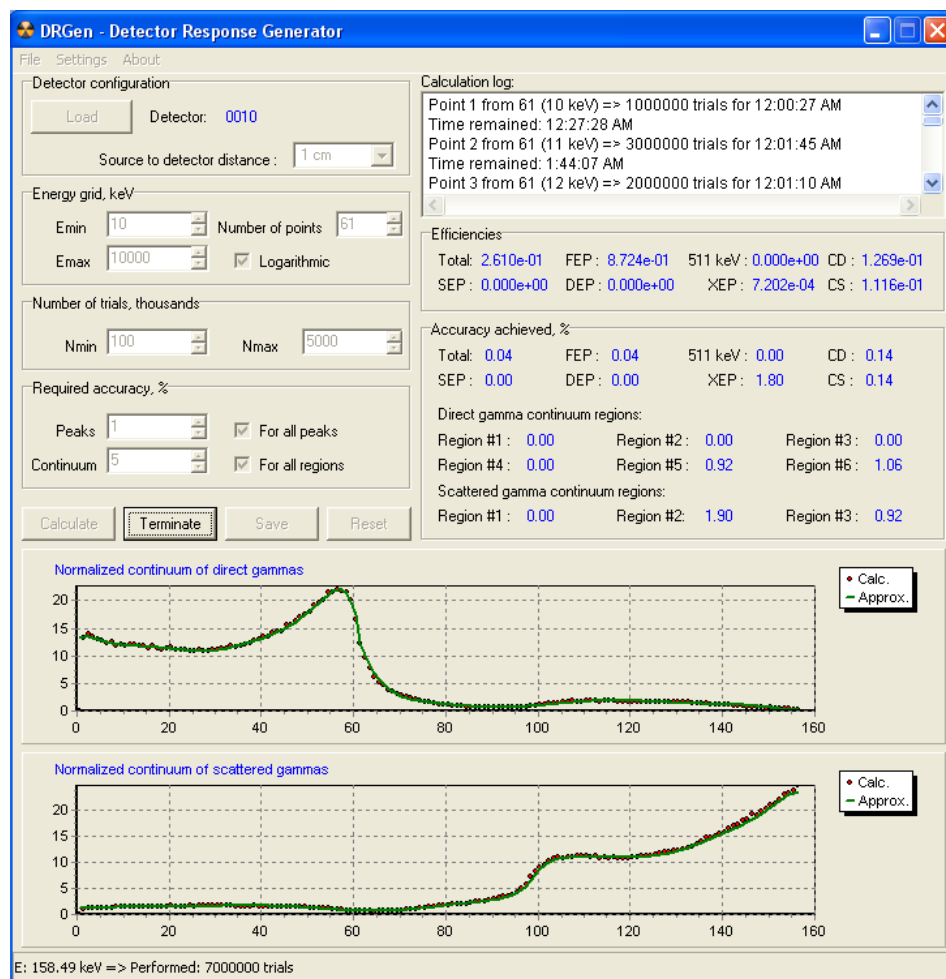
- Peak-to-Total efficiency ratios for FEP, SEP, DEP, XEP, and 511 keV annihilation peak
- Continuum-to-Total efficiency ratios for Compton continuum and Backscatter „peak“ distribution
- Parameterized shapes of Compton continuum and Backscatter „peak“ distribution

Scope:

- Detectors: **NaI** and High Pure Ge (**HPGe**)
- Crystal length and diameter grid: **20 mm – 120 mm** with 10 mm step
- Photon energy grid: 61 points, **10 keV – 10 MeV**
- Source-to-detector distance grid: **0 mm, 10 mm, 50 mm, 250 mm**
- Total number of profiles generated: $2 \times 121 \times 61 \times 4 = 59048$



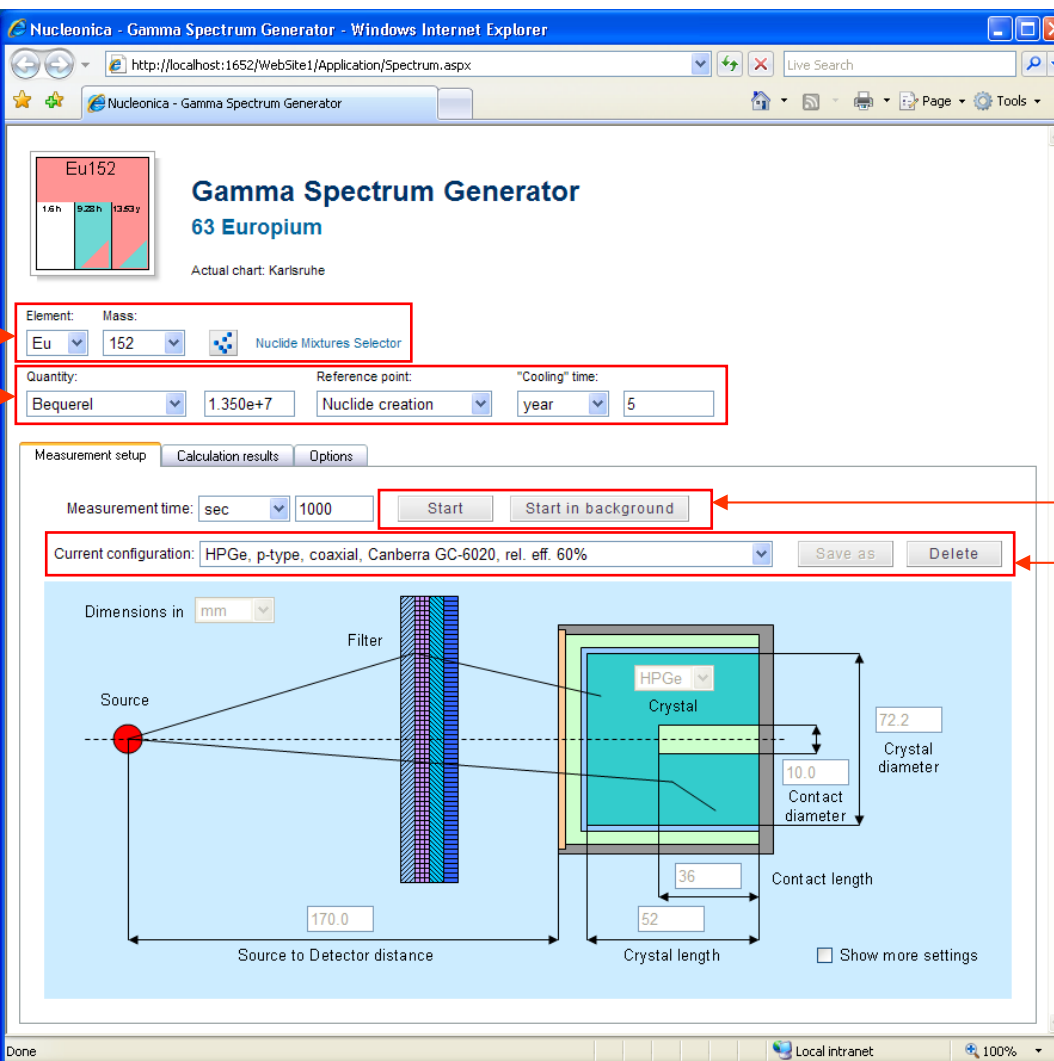
DRGen (Detector Response Generator): creating the Detector Reference Response Profile Database



Features implemented: Measurement setup

An arbitrary individual nuclide or a pre-defined mixture of nuclides can be selected as a radiation source

The quantity (activity, mass or number of atoms) of a nuclide or a mixture can be specified either at the moment of its production or at the spectrum measurement starting point of time. In the former case controls for specifying duration of a source cooling time interval become available.



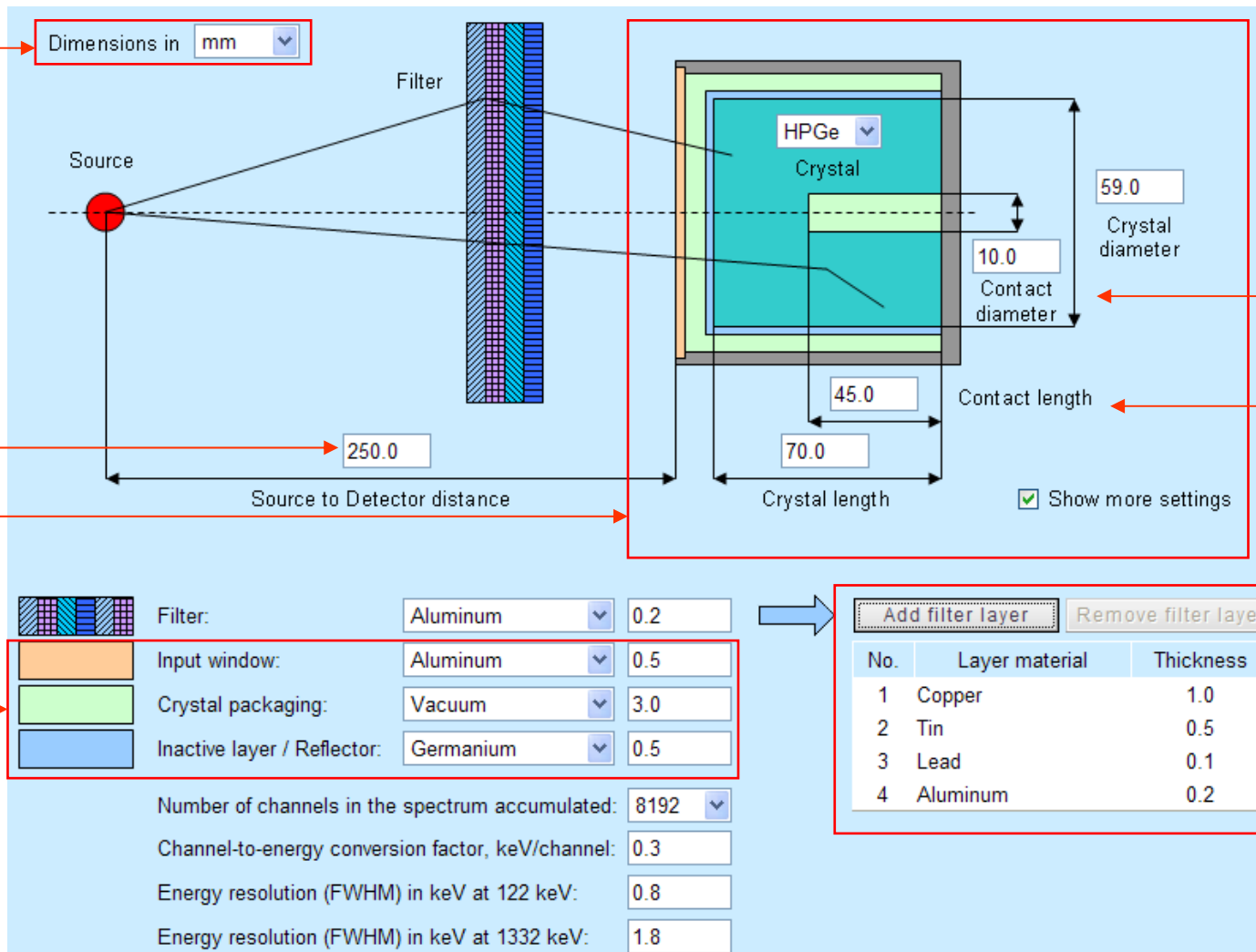
Calculations can be started on-line or in a background mode

A suitable γ -spectrometer can be chosen from 6 pre-defined configurations, which include 2 coaxial HPGe (50% and 150%) detectors, low-energy (LEGe) and broad-energy (BEGe) HPGe detectors, and 2 NaI detectors ($\varnothing 3'' \times 3''$ and $\varnothing 2'' \times 1''$). In addition, user's specific configurations can be managed.

Features implemented: Measurement setup

Dimensions can be entered in "mm", "cm" or "inch" units

The configurable parameters include the source-to-detector distance, as well as dimensions and materials of the detector construction elements.



Dimensions in

Source

Filter

HPGe

Crystal

59.0
Crystal diameter

10.0
Contact diameter

45.0
Contact length

70.0
Crystal length

250.0
Source to Detector distance

☒ Show more settings

Filter: 0.2

Input window: 0.5

Crystal packaging: 3.0

Inactive layer / Reflector: 0.5

Number of channels in the spectrum accumulated:

Channel-to-energy conversion factor, keV/channel:

Energy resolution (FWHM) in keV at 122 keV:

Energy resolution (FWHM) in keV at 1332 keV:

Add filter layer Remove filter layer

No.	Layer material	Thickness
1	Copper	1.0
2	Tin	0.5
3	Lead	0.1
4	Aluminum	0.2

The dimensions of a cylindrical contact at the rear side of the crystal (a construction feature of conventional coaxial HPGe detectors) can be specified


Up to 6 additional absorbing filters made of Al, Cu, Fe, Pb, Sn, or polyethylene can be placed between source and detector

Features implemented: Options

Nucleonica - Gamma Spectrum Generator - Windows Internet Explorer

http://localhost:1652/WebSite1/Application/Spectrum.aspx#

Nucleonica - Gamma Spectrum Generator

 **Gamma Spectrum Generator**
Natural Uranium
Actual chart: Karlsruhe

Nuclide Mixtures:
Natural Uranium Nuclide Selector

Total activity:
Bequerel 2.557e+004

Reference point:
Measurement start

Measurement setup Calculation results Options

Gamma Spectrum Generator Settings:

- ☒ Display detector efficiency curves
- ☒ Consider decay transformations during cooling and counting time intervals
 - ☒ Include gamma-rays of daughter nuclides
 - 0.01 Decay Engine's accuracy factor
- ☒ Consider effects of backscatter radiation
 - 1.0 Backscatter peak normalisation factor

Done Local intranet 100%

Efficiency Graph
can be activated
in the Calculation
Results output

The backscatter
peak simulation
can be switched
on/off, and its
contribution to
the spectrum can
be adjusted

Decay
calculations can
be enabled that
will allow
contributions
from decay
products, being
accumulated
during source
cooling and
spectrum
measurement
time intervals

Features implemented: Calculation results

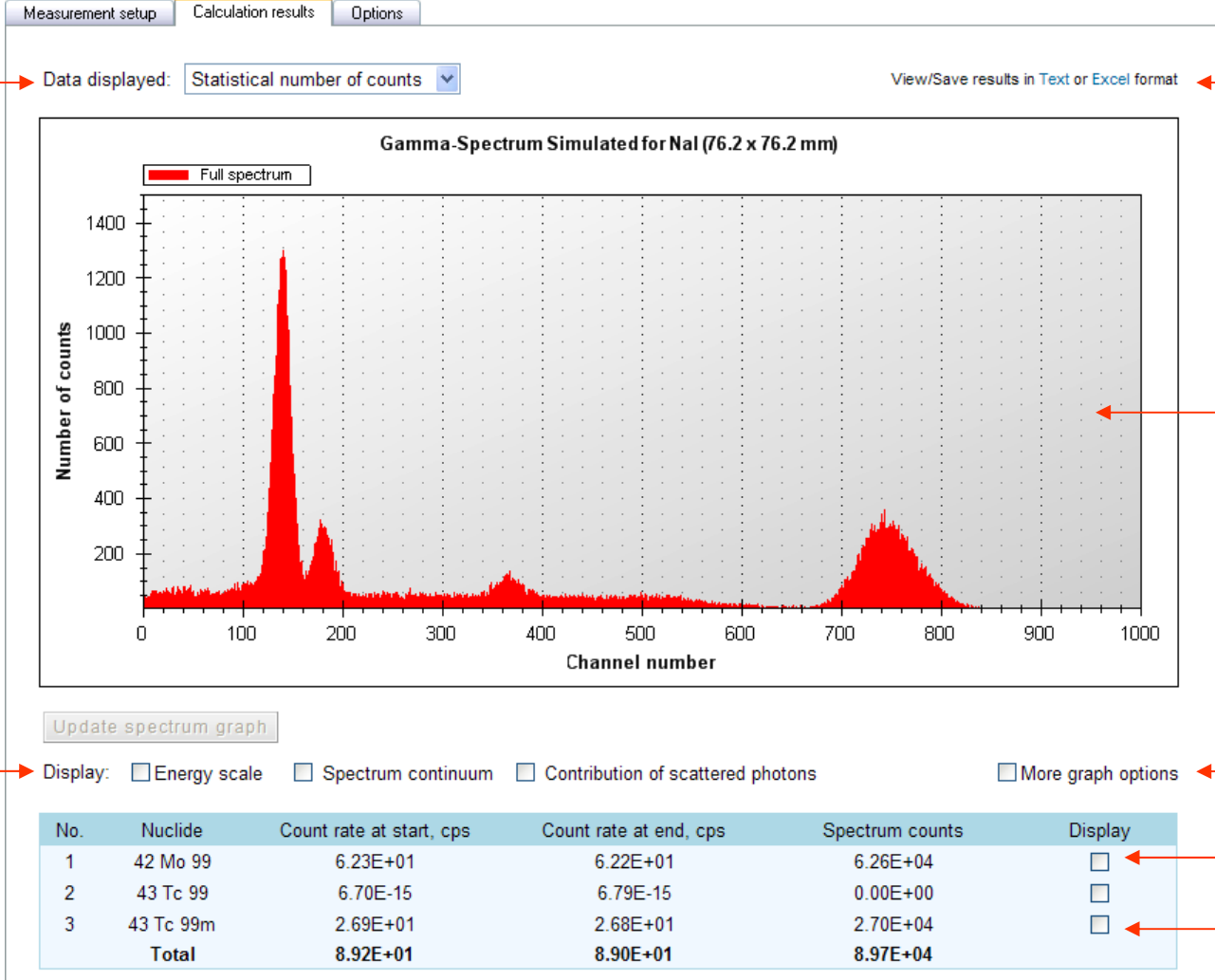
Statistical number of counts

Count rate at start

Count rate at end

Theoretical number of counts

Statistical number of counts



Measurement setup | **Calculation results** | Options

Data displayed: Statistical number of counts

View/Save results in Text or Excel format

Gamma-Spectrum Simulated for NaI (76.2 x 76.2 mm)

Number of counts

Channel number

Full spectrum

Update spectrum graph

Display: ☐ Energy scale ☐ Spectrum continuum ☐ Contribution of scattered photons ☐ More graph options

No.	Nuclide	Count rate at start, cps	Count rate at end, cps	Spectrum counts	Display
1	42 Mo 99	6.23E+01	6.22E+01	6.26E+04	<input type="checkbox"/>
2	43 Tc 99	6.70E-15	6.79E-15	0.00E+00	<input type="checkbox"/>
3	43 Tc 99m	2.69E+01	2.68E+01	2.70E+04	<input type="checkbox"/>
Total		8.92E+01	8.90E+01	8.97E+04	

Complete set of spectral information can be downloaded as a text or Excel spreadsheet file

Right click within the graph area enables a context menu, from which one can print or download the spectrum graph

Additional options allow to customize appearance of the graph to meet one's needs and requirements

Display nuclide specific contributions to the full spectrum

Switch between channel number and energy scale; show peak, continuum and backscatter peak contributions to the full spectrum

Calculation results : Detailed Spectral Data in Excel Spreadsheet

Calculation Parameters

Nucleonica - GAMMA SPECTRUM GENERATOR Version 1.0.0.1			
File content: Calculation Results			
Created: 4/17/2008 3:21:29 PM (UTC)			
SPECTROMETER:			
Configuration name	Noname		
Crystal type	HPGe		
Crystal length	52.00	mm	
Crystal diameter	72.20	mm	
Contact length	36.00	mm	
Contact diameter	10.00	mm	
Inactive layer	0.90	mm	Germanium
Crystal packaging	5.00	mm	Vacuum
Detector input window	1.50	mm	Aluminum
Number of additional filters	0.00		
Filter No.1	0.00	mm	
Filter No.2	0.00	mm	
Filter No.3	0.00	mm	
Filter No.4	0.00	mm	
Filter No.5	0.00	mm	
Filter No.6	0.00	mm	
FWHM at 122 keV			
FWHM at 1332.5 keV			
Number of channels			
Channel-to-Energy conversion			
Source-to-Detector distance			
Spectrum measurement time			
SOURCE:			
Nuclide	56 Ba 137m		
Quantity	1		
Reference point of time	N		
Source cooling interval	30	min	
CALCULATION:			
Consider decay transformations	Yes		
Include gammas of daughter nuclides	Yes		
Decay engine's accuracy factor	0.01		
Consider backscatter radiation	Yes		
Backscatter peak normalization factor	2		

Nuclide Specific Data

Nuclide	Ancestor	Activity, Bq		Number of decays	Count rate, cps		Number of counts	
		at start	at end		at start	at end	theor.	statist.
55 Cs 137	55 Cs 137	1.000E+00	1.000E+00	1.000E+00	5.652E-08	5.652E-08	5.652E-08	0.000E+00
56 Ba 137m	55 Cs 137	9.437E-01	9.395E-01	9.416E-01	7.177E-03	7.144E-03	7.160E-03	0.000E+00
TOTAL:		0.000E+00	0.000E+00	0.000E+00	7.177E-03	7.144E-03	7.160E-03	0.000E+00

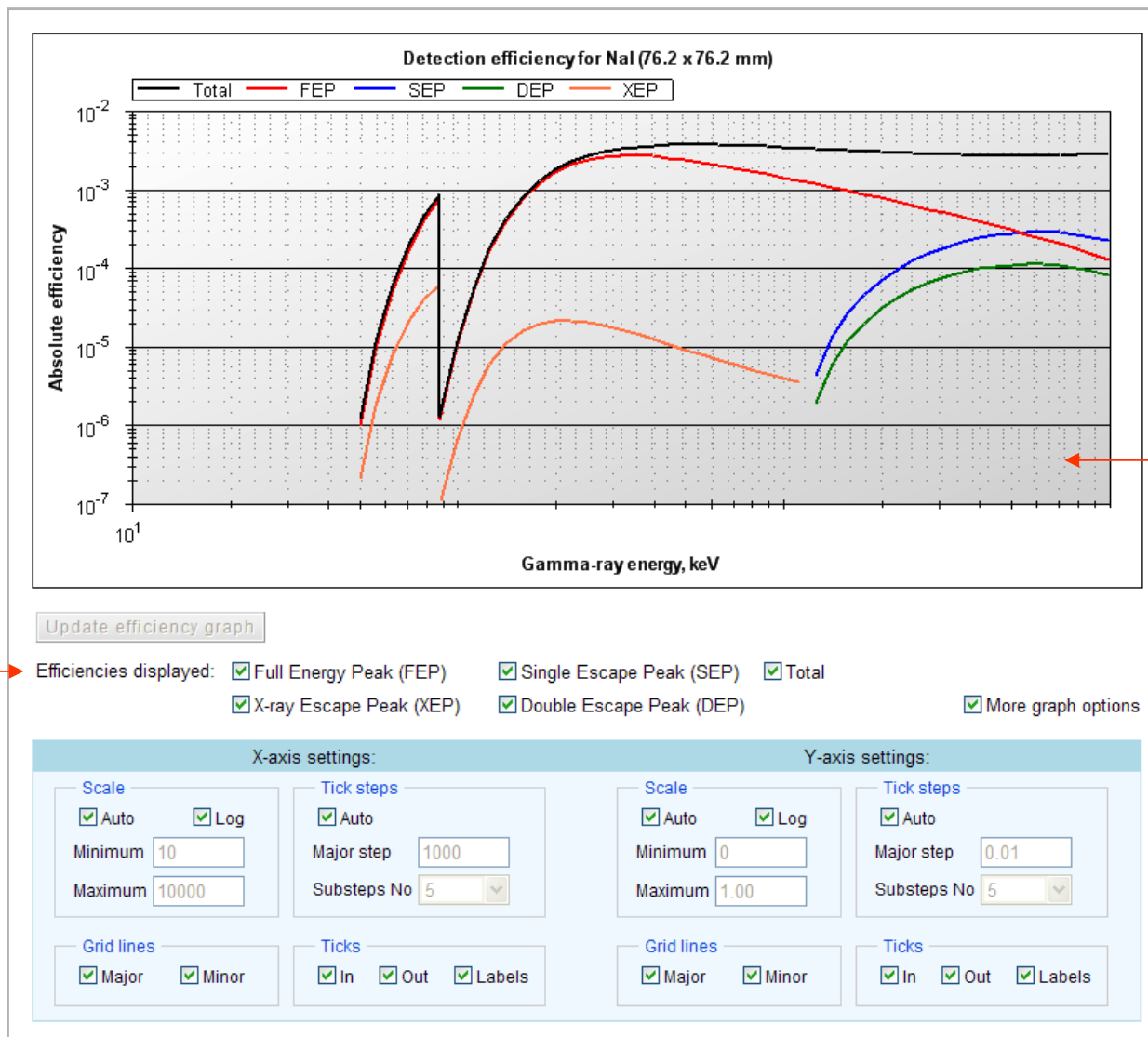
Gamma and X-ray Data

Energy, keV	X/G ray	Emission rate, 1/s		Photons emitted	Peak region counts		Detection efficiency		Ancestor's MDA(B), Bq
		at start	at end		peak area	peak bkg	total	FEP	
3.50	G	5.800E-06	5.800E-06	5.800E-06	2.715E-08	4.094E-05	7.530E-03	4.681E-03	1.441E+08
47	X	9.837E-03	9.793E-03	9.815E-03	0.000E+00	2.757E-05	0.000E+00	0.000E+00	NAN
82	X	1.951E-02	1.943E-02	1.947E-02	5.198E-07	3.363E-05	2.775E-05	2.676E-05	9.635E+08
19	X	3.600E-02	3.584E-02	3.592E-02	1.137E-06	3.301E-05	3.285E-05	3.171E-05	1.997E+08
40	X	1.310E-02	1.304E-02	1.307E-02	2.193E-06	3.211E-05	1.727E-04	1.681E-04	5.304E+07
166	G	8.500E-01	8.462E-01	8.481E-01	1.960E-03	2.144E-06	6.715E-03	2.311E-03	1.964E+03

Gamma Spectrum

Energy, keV	Count rate at start, cps			Count rate at end, cps			Theoretical number of counts		
	Continuum	Scattered	Total	Continuum	Scattered	Total	Continuum	Scattered	Total
0.20	2.637E-06	8.042E-07	2.650E-06	2.637E-06	8.006E-07	2.638E-06	2.631E-06	8.024E-07	2.644E-06
0.60	3.185E-06	9.725E-07	3.218E-06	3.171E-06	9.681E-07	3.204E-06	3.178E-06	9.703E-07	3.211E-06
1.00	3.335E-06	1.019E-06	3.376E-06	3.320E-06	1.015E-06	3.360E-06	3.327E-06	1.017E-06	3.368E-06
1.40	3.381E-06	1.035E-06	3.394E-06	3.366E-06	1.030E-06	3.379E-06	3.373E-06	1.032E-06	3.387E-06
1.80	3.400E-06	1.042E-06	3.401E-06	3.385E-06	1.037E-06	3.385E-06	3.392E-06	1.039E-06	3.393E-06
2.20	3.411E-06	1.046E-06	3.411E-06	3.396E-06	1.042E-06	3.396E-06	3.404E-06	1.044E-06	3.404E-06
2.60	3.421E-06	1.050E-06	3.421E-06	3.405E-06	1.046E-06	3.405E-06	3.413E-06	1.048E-06	3.413E-06

Calculation results : Detection Efficiency



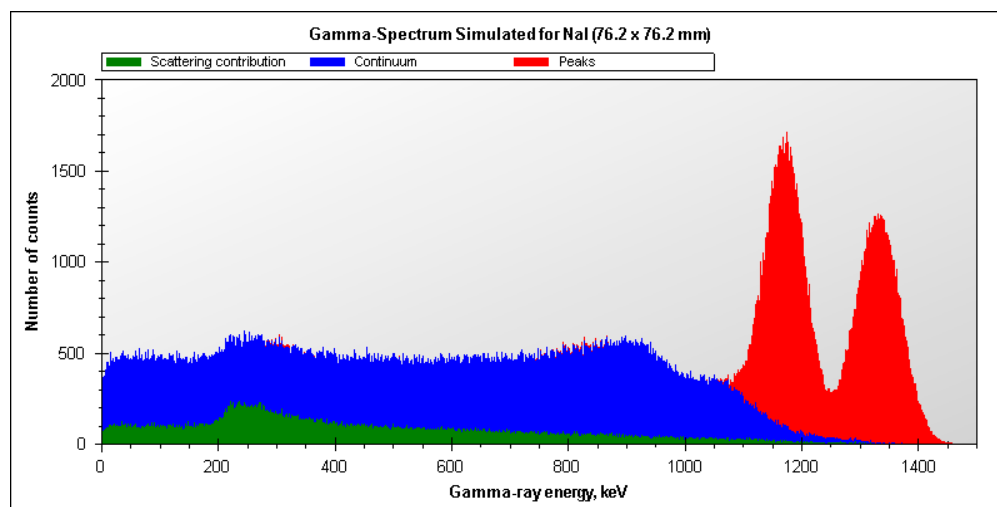
Select efficiency data to be displayed on the graph

Right click within the graph area enables a context menu, from which one can print or download the efficiency graph

Additional options allow to tailor the efficiency graph to one's needs and requirements

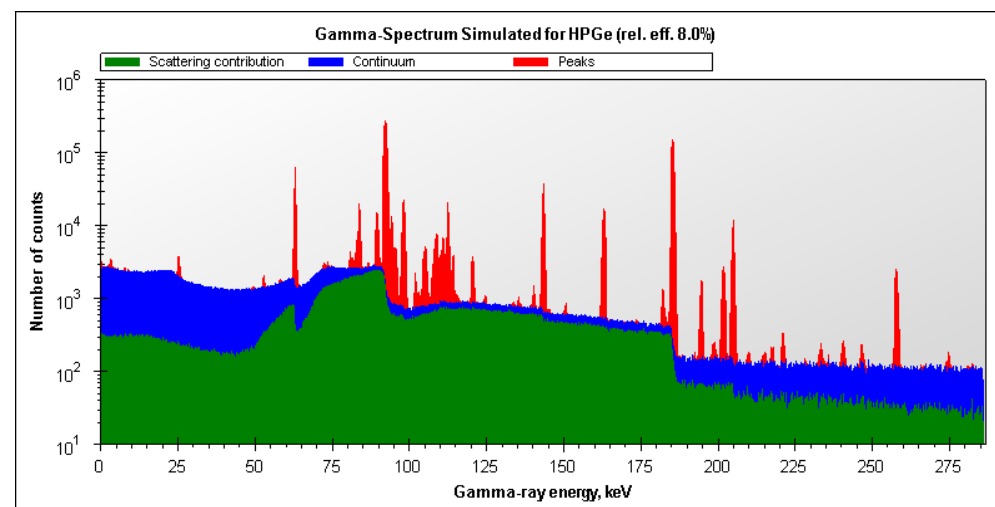
Examples:

100 kBq ^{60}Co



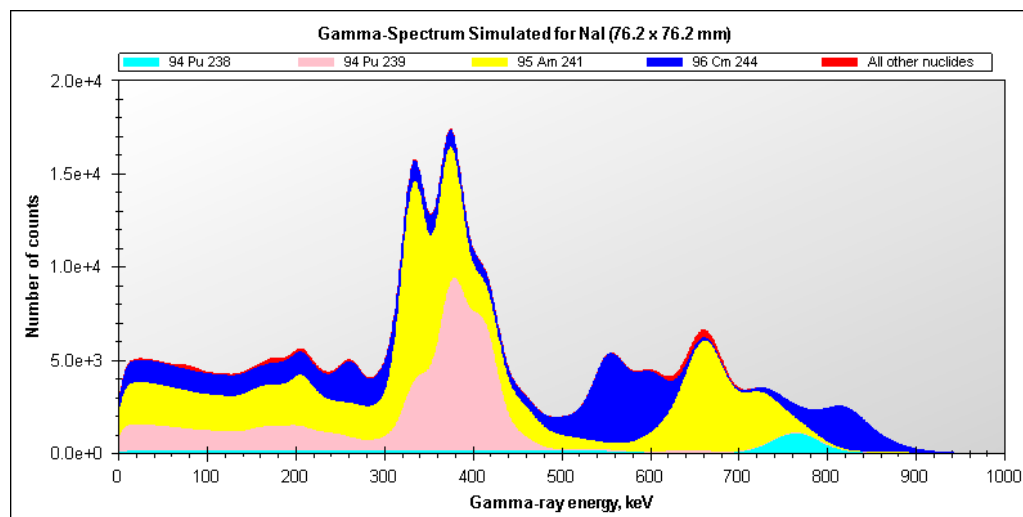
Detector - NaI ($\varnothing 3'' \times 3''$)
Source-to-detector distance - 25 cm
Measurement time - 1000 s

1 g Nat U (2 years after separation)

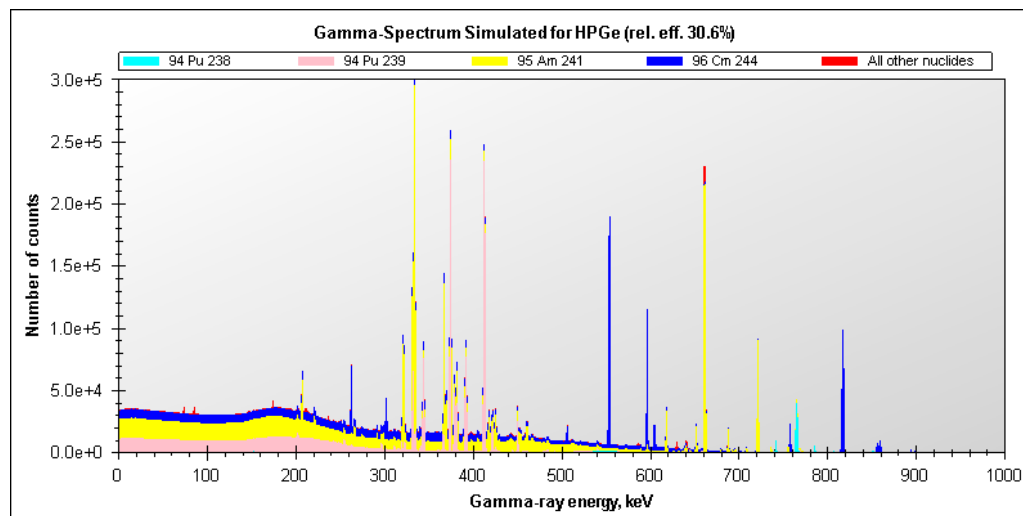


Detector – LEGe (20 mm x 2800 mm²)
Source-to-detector distance – 25 mm
Filter – 0.5 mm Sn
Measurement time - 10⁵ s

Examples:



Detector – NaI (Ø3"×3")
Source-to-detector distance – 25 cm
Filter – 5 mm Pb
Measurement time - 1000 s





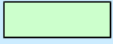

Actinides extracted from 1 kg 6-year-aged PWR spent fuel. Activity - 5.25 TBq

Detector – BEGe (30% rel. eff.)
Source-to-detector distance – 25 cm
Filter – 5 mm Pb
Measurement time - 1000 s

Current work:

- Including background gamma spectrum from naturally occurring radionuclides, which will make the spectrum shape and MDA evaluations more realistic.

Additional measurement setup properties:

	Absorbing filter layers:	Aluminum	1.0	Add	Del	No.	Layer material	Thickness
	Input window:	Aluminum	0.5					
	Crystal packaging:	Foam Plastic	0.0					
	Inactive layer / Reflector:	Aluminium oxide	0.5					

ADC and energy resolution parameters:

2048	Number of spectrum channels	18.0	Energy resolution (FWHM) at 122 keV, keV
1.0	Channel-to-energy conversion factor, keV/channel	90.0	Energy resolution (FWHM) at 1332 keV, keV

Background gamma-ray peak and continuum intensities, cps:

0.013	Count rate in 185.7 keV peak of U-235	0.0003	Count rate in 661.6 keV peak of Cs-137
0.012	Count rate in 238.6 keV peak of Pb-212 (Th-232)	0.00015	Count rate in 1332.5 keV peak of Co-60
0.035	Count rate in annihilation 511.0 keV peak	0.02	Count rate in 1460.8 keV peak of K-40
0.008	Count rate in 609.3 keV peak of Bi-214 (U-238)	3	Continuum count rate (0 - 3 MeV)

Measurement setup Calculation results Options

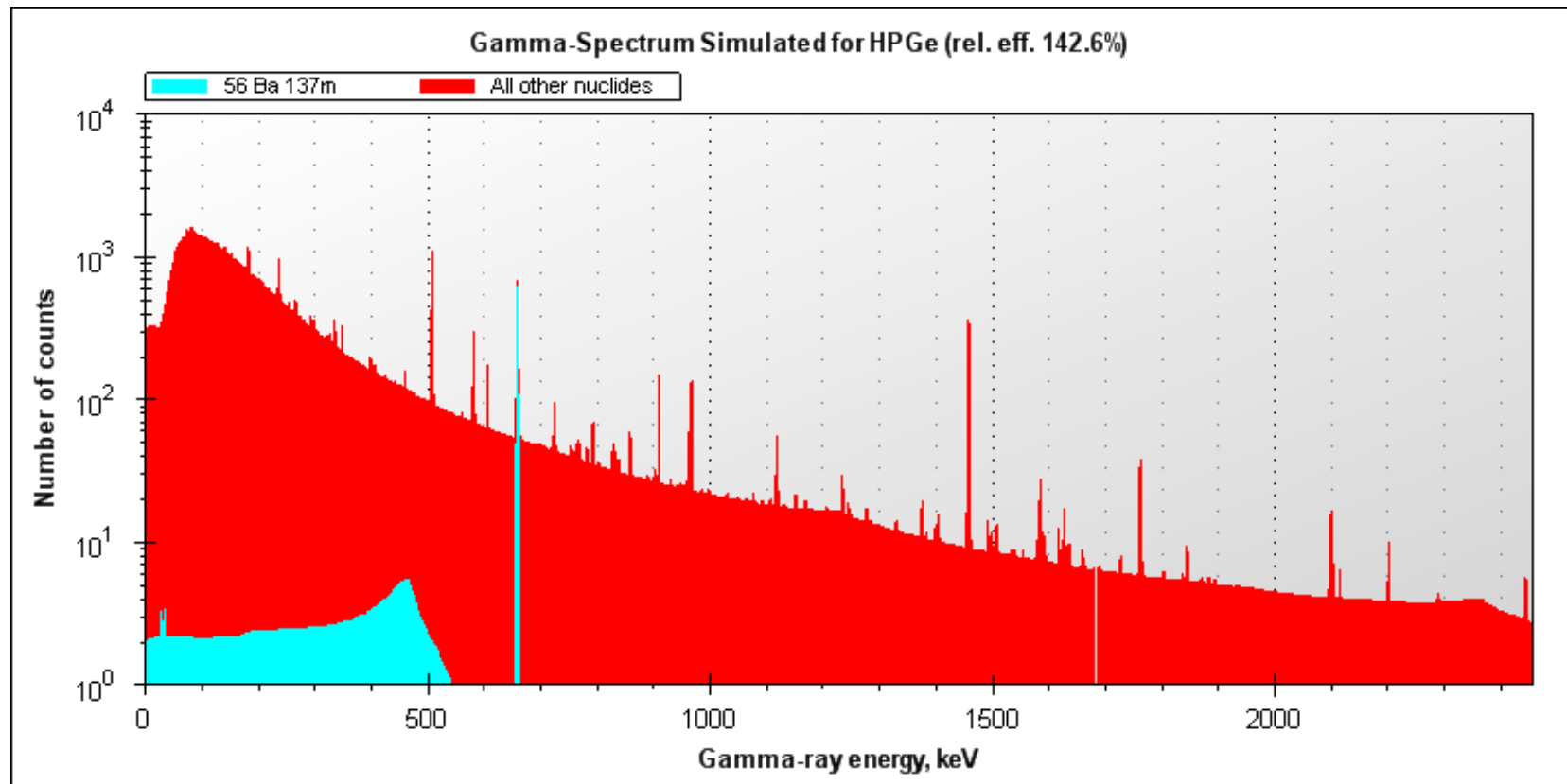
Gamma Spectrum Generator Settings:

- ☐ Display detector efficiency curves
- ☐ Consider decay transformations during cooling and counting time intervals
- ☐ Consider effects of backscatter radiation
- ☐ Consider bremsstrahlung photon creation
- ☒ Simulate natural gamma-ray background

A respective option has to be selected on „Options“ tab to enable the background simulation

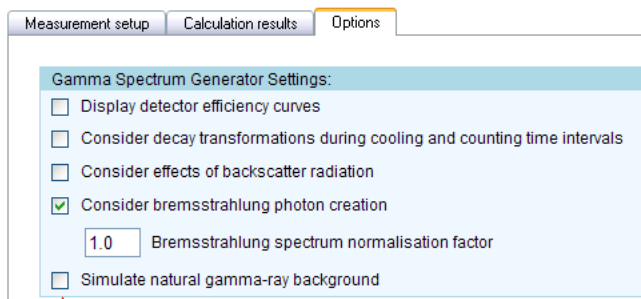
Current work: Natural background simulation

- a 10 Bq ^{137}Cs source at 10 mm distance from 150% HPGe with natural background photons included



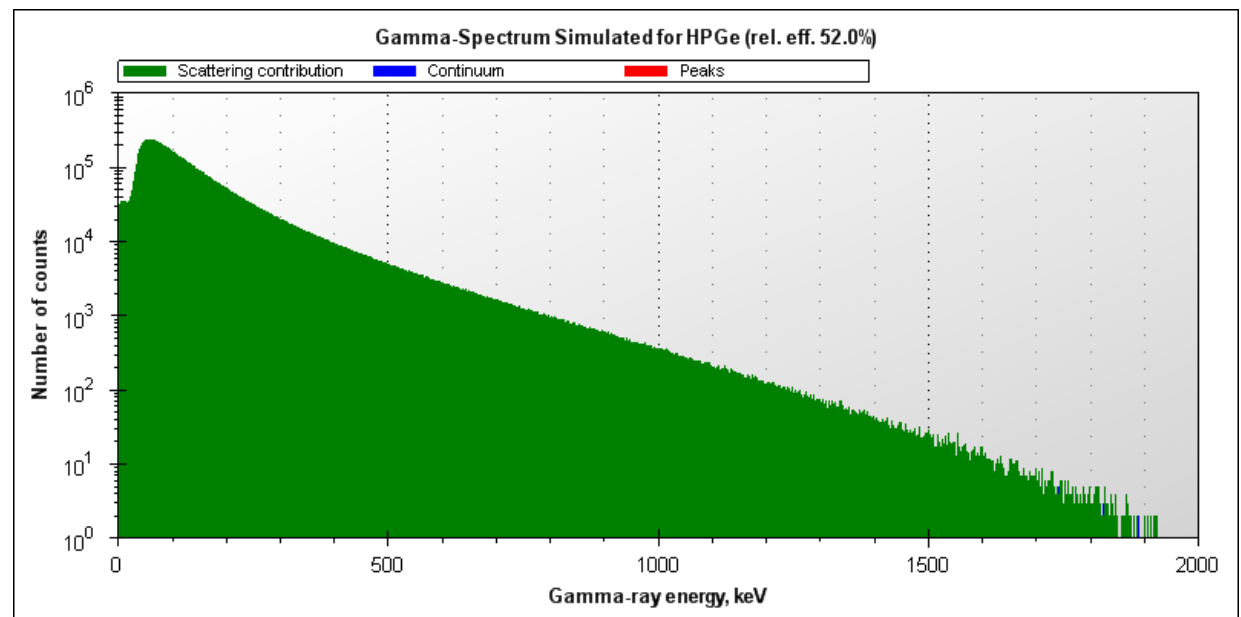
Current work:

- Bremsstrahlung simulation



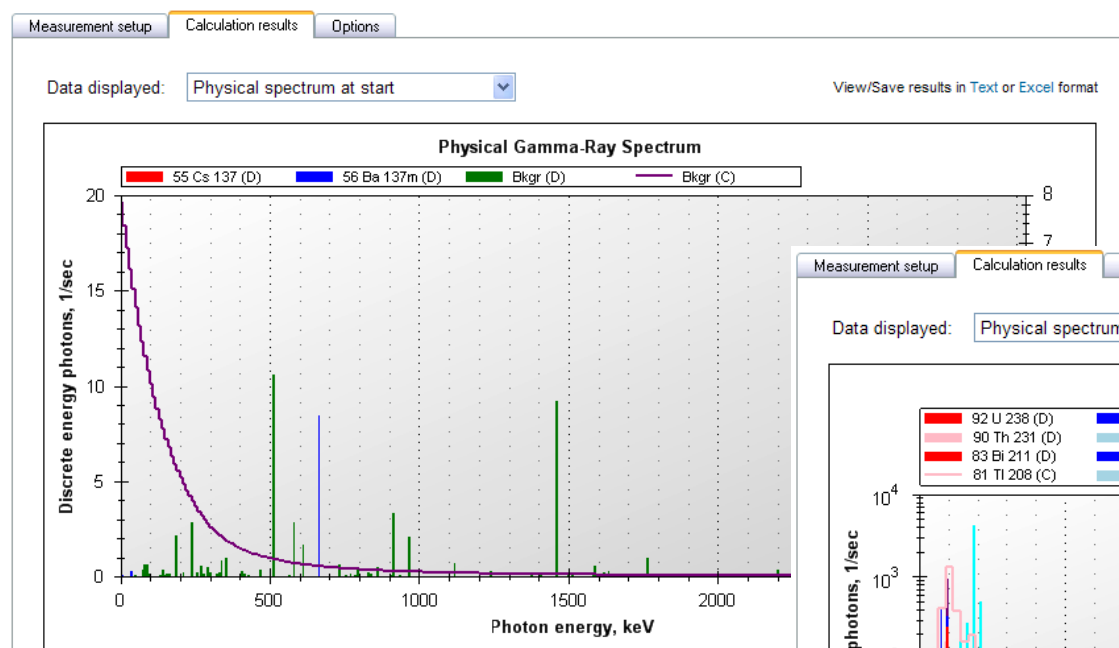
A respective option can be selected on „Options“ tab to enable the bremsstrahlung simulation.

A gamma-spectrum simulated for the 10 MBq ^{90}Sr - ^{90}Y source and 50% HPGe



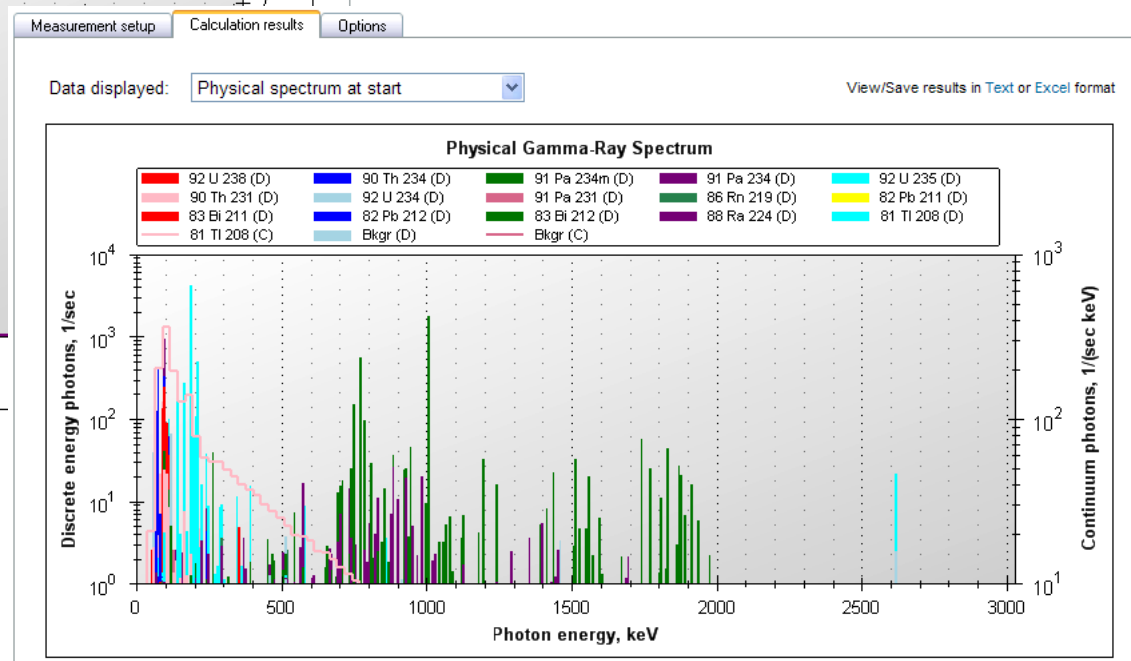
Current work:

- Physical photon spectrum visualization



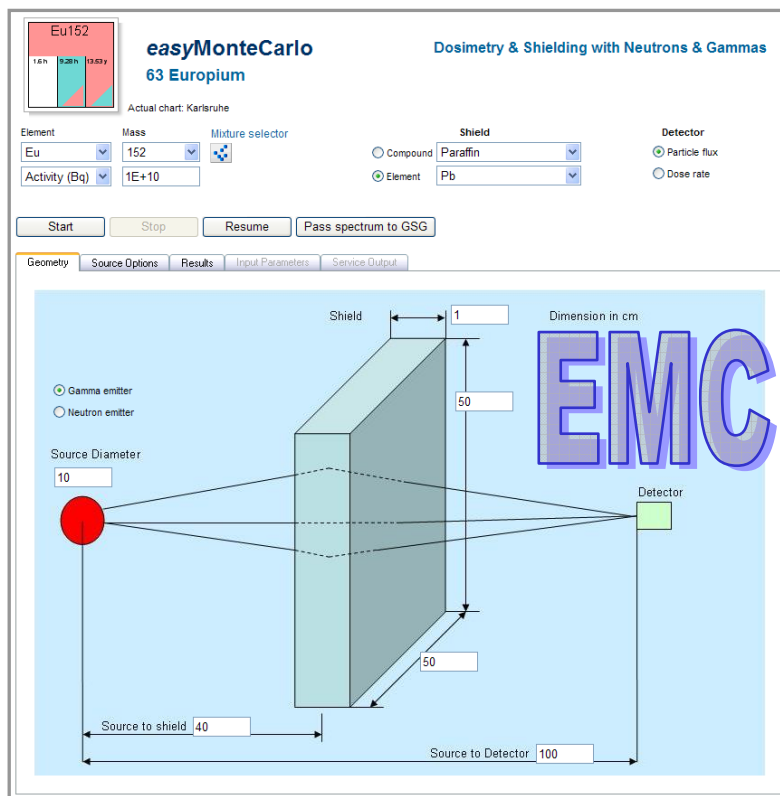
¹³⁷Cs source and natural background photons

4.46% Uranium source and natural background photons



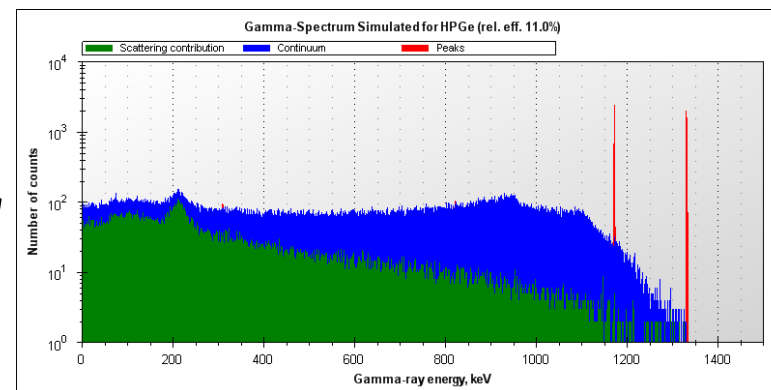
Current work:

- Including self-attenuation and scattering effects, which would allow more realistic simulation of gamma-spectra from voluminous and shielded sources.

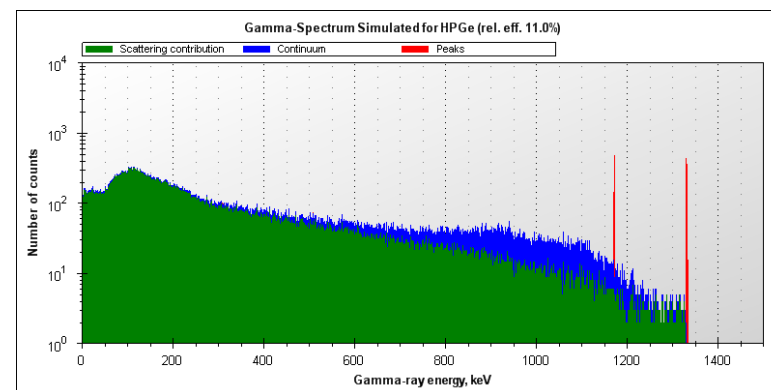


EMC → GSG

Unshielded ^{60}Co :



^{60}Co behind 12 cm Al shield:



Current work:

- Extending the detector response profile database to include LaBr_3 scintillators that, because of their much superior energy resolution, start to replace traditional NaI crystals in many applications.

Future work:

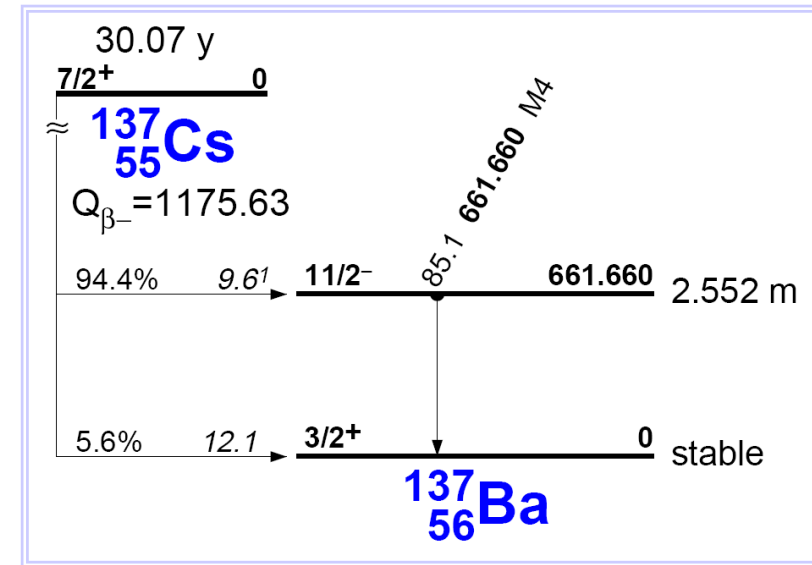
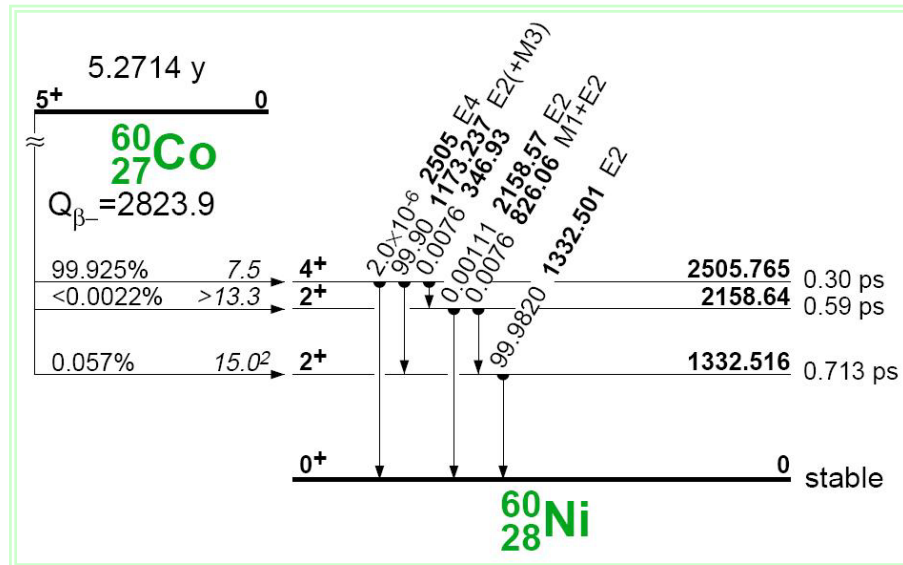
- Include simulation of the spectrum distortion effects (e.g. due to coincidence summing and energy resolution deterioration), which may appear in measurements involving elevated count rates and small source-to-detector distances.

Thank you for your attention !



Exercises:

- The measurement setup is similar to the default configuration “NaI, L × D = 1 in × 2 in (default)”. You are going to calibrate it using the 1 MBq ^{60}Co and 1 MBq ^{137}Cs reference gamma sources. Approximately, how many statistical counts can you expect within 100 s in the corresponding gamma-spectra? Make the evaluations with and without backscattered photon contribution.



Answer: ^{60}Co - without backscatter photons $\approx 1.66 \cdot 10^5$ and with backscatter photons $\approx 1.91 \cdot 10^5$ counts,
 ^{137}Cs - without backscatter photons $\approx 1.06 \cdot 10^5$ and with backscatter photons $\approx 1.18 \cdot 10^5$ counts.

Exercises:

2. You have to measure the 10 MBq ^{152}Eu source with NaI (3"×3") scintillation detector in the measurement setup similar to the default configuration "NaI, $L \times D = 3 \text{ in} \times 3 \text{ in}$ (default)". In your disposal there are three lead filters – 1 mm, 3 mm and 5 mm thick. Find the right combinations of the filters, which would make the measurement possible, assuming that your electronics can cope only with input count rates below 20 kcps (kilo counts per second). Check if the same electronics and filters will allow you to perform the measurement in the configuration "HPGe, coaxial, p-type, rel. eff. 150% (default)".

**Answer: Valid filter combinations: 3 mm + 5 mm (18.8 kcps) and 1 mm + 3 mm + 5 mm (17.2 kcps).
The electronics is not suitable for the configuration with 150% HPGe detector since even for the thickest filter combination the predicted input count rate is 22.6 kcps.**

3. What is the relative efficiency of the HPGe detector with crystal length – 30 mm, crystal diameter – 50 mm, rear contact length – 20 mm, rear contact diameter – 10 mm, inactive Ge – 1.5 mm, cap thickness – 1 mm Al, and crystal to cap distance – 5 mm? What crystal length doubles the detector relative efficiency?

Answer: Relative efficiency = 10.5%. Crystal length $L = 46.5 \text{ mm}$ gives 21% relative efficiency.

Exercises:

4. The 1 g natural uranium sample (^{234}U – 0.000055 g, ^{235}U – 0.0072 g, ^{238}U – 0.992745 g) was measured twice on the same NaI (3"×3") scintillation spectrometer (configuration "NaI, L × D = 3 in × 3 in (default)"). The first and the second measurements were performed for 100000 s respectively 10 days and 1 year after the uranium separation. What are the relative contributions of ^{235}U and ^{238}U to the gamma-spectrum measured in both cases? When modeling the spectra, use 1 mm Pb filter to imitate the self-attenuation properties of the sample.

Answer: After 10 days ^{235}U - 76% and ^{238}U - 24%; after 1 year ^{235}U - 46% and ^{238}U - 54%.

5. Based on the gamma-spectrometric examination of a source, the presence of ^{60}Co with activity 100 kBq was revealed. Which of the default GSG measurement configurations are suitable for detecting an additional presence of 50 Bq of ^{241}Am in the same source by performing a 1000 s long measurement?

Answer: Configurations with LEGe and BEGe detectors. The respective MDAs are 12,2 Bq and 18,6 Bq.